TRANSACTIONS
OF
The Optical Society.

VOL. XVII. DECEMBER, 1916. No. 3.

Meeting, 14th December.

F. J. CHESHIRE, Esq., F.R.M.S., President, in the Chair.

The following were balloted for, and duly elected to the Society:—

AS MEMBERS.

F. S. Berrett; Messrs. Dollond & Co., London.
C. Lees Curties; Messrs. Charles Baker, London.
F. S. B. Ellis, West Croydon.
J. W. Hasselkus; Messrs. Ross, Ltd., London.
Prof. Herbert Jackson, F.I.C., King's College, London.
Horace Lee, B.A.; Messrs. Taylor, Taylor & Hobson, Leicester.
Thos. R. Merton, D.Sc., King's College, London.
Prof. John W. Nicholson, M.A., D.Sc., King's College, London.
L. V. Riquez; Messrs. Dollond & Co., London.
William Simms; Messrs. Troughton & Simms, Blackheath.

AS STUDENT MEMBER.

Eric L. Ebbage, Northampton Polytechnic Institute.

The undermentioned candidates were proposed for election as Members, the name of the proposer from personal knowledge being appended:—

Lionel B. Booth, M.A., F.R.A.S., Farnborough (T. Smith).
David Bradfield, North Finchley (W. Shackleton).

Thomas Charles, London (The President).
Michael B. Field, M.Inst.C.E., Glasgow (The President).
Patrick A. Gibney, Dublin (Sir Howard Grubb, F.R.S.).
C. L. Redding, London (S. D. Chalmers).
Julius Rheinberg, London (The President).
F. Parker Wood, London (T. F. Connolly).
R. S. Wright, London (The President).

The following papers were read and discussed :—

ON THE REFRACTOMETRY AND IDENTIFICATION OF GLASS SPECIMENS—ESPECIALLY LENSES.

By Mr. L. C. Martin, D.I.C., A.R.C.Sc., B.Sc.,
Imperial College of Science and Technology.

Existing methods in accurate glass refractometry usually demand some special condition on the part of the specimens tested, and in general at least one plane polished face is required. The refractive indices of single lenses may of course be roughly determined from measurements of the focal length and dimensions of the lens. Since, however, the exact determination of a focal length is an ideal measurement involving the use of rays indefinitely close to the axis, and since the paths of rays through the system cannot conveniently be investigated by other means, the determination of refractive index in such cases is a matter of uncertainty. With regard to rough and unpolished blocks no satisfactory method seems to have been devised.

Especially in the case of lenses it is desirable to have a ready method of determining the refractive index. This would be of use in optical laboratories for the identification of lenses, and also for the copying of optical systems, particu-

larly if the method will allow of the determination of dispersion. The method about to be described appears to be satisfactory for such purposes, and with moderate care refractive indices may be obtained accurate to about 1 in the 4th decimal place; also the determination may be made with the usual sources of light—a sodium flame and a hydrogen tube.

The principle of immersion used in the method is by no means new, but considerable difficulties have hitherto been experienced in the use of liquids or mixtures of liquids for optical measurements, owing to their liability to changes of refractive index due to variations of temperature and concentration. These difficulties have been overcome in the method to be described. Its fundamental principle is extremely simple.

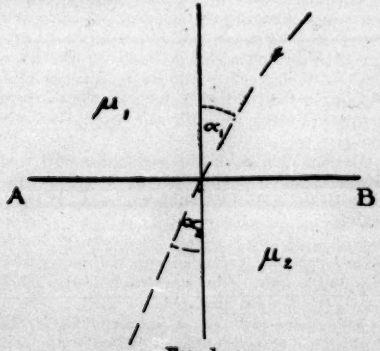

FIG. 1

If the line AB represents a small portion of the bounding surface of two media, α_1 and α_2 the angles of incidence and refraction of a ray of light, and μ_1, μ_2 the refractive indices of the two media,

$$\mu_1 \sin \alpha_1 = \mu_2 \sin \alpha_2.$$

If $\mu_1 = \mu_2$ the ray will suffer no deviation, and it can be proved also that there will be no reflection. With these considerations we can easily see that if a specimen be immersed in a liquid of the same refractive index (considering light of one frequency only) the system will be optically homogeneous, and objects seen through the specimen when immersed in the liquid will not appear distorted. We now have a method of obtaining the refractive index of a specimen if we can obtain the refractive index of the liquid when the necessary equality has been attained. Evidently we must seek some methods of varying and measuring the refractive index of a liquid, and also some suitable way of observing the equality.

A Liquid of Adjustable Refractive Index.

The refractive index of a liquid may be varied by changing its temperature, but a more convenient method is to employ a mixture of two liquids in which a change in the proportion of one to the other produces a corresponding change in the refractive index of the mixture; a solution whose strength can be adjusted may serve.

Carbon disulphide mixes in all proportions with alcohol or benzol. As glass will presumably be the principal subject of test, it is important to be able to make the index of the liquid as high as possible, so as to make it suitable for most optical glasses. Using carbon disulphide we may increase the index to 1.6277 at 20° C. for sodium light.

This value will prove high enough for the majority of glasses, but some difficulty may arise when measuring the index for the C line for a few glasses owing to the high dispersive power of carbon disulphide. The refractive index for D will become very high when the concentration is increased sufficiently to equalise the indices for the C line. Except for extra dense flints, however, with refractive indices above 1.625

(D), carbon disulphide may be used, and may even be employed for higher values if cooled; thus at 0° C. its index becomes 1.6433.

With a mixture of carbon disulphide and alcohol the refractive index can be varied from 1.3617 to 1.6277. With benzol the range is from 1.5003 to 1.6277. The range of usefulness of these liquids will be seen. Both mixtures have the advantage that the evaporation of the constituents generally takes place unequally; hence the refractive index will change very gradually and conveniently. This makes the final determination easier and more exact.

Unfortunately the vapour of carbon disulphide is of a somewhat poisonous character, and experiments with it must not be performed in the open. The constant inhalation of small quantities produces headache and neuralgia. This difficulty may be overcome by using the apparatus in a stink cupboard, or by arranging a fan to blow the vapour away from the observer.

As a substitute for this mixture it is possible to use a solution of mercuric iodide in potassium iodide. When fully concentrated the refractive index increases to about 1.7. The solution is a heavy yellow liquid, but it is fairly mobile, and is used in determinations of specific gravity. It has rather a bad action on the skin. The mercuric iodide should be dissolved in a saturated solution of potassium iodide. To decrease the refractive index it is convenient to dilute with methylated spirit, which can more quickly be removed by evaporation when it is desired to concentrate the solution once more. The liquid is strongly hygroscopic, and this action will delicately vary the refractive index, although somewhat slowly.

It has not at present been found easy to use this yellow liquid for measurements with the 'F' hydrogen line as the luminosity of the spectrum in this region is greatly diminished

when the light is passed through the solution. The C and D lines are quite bright. In this connection it may be noted that a knowledge of the index for these lines should often be sufficient to identify the chief characteristics of a glass which a knowledge of the value for D alone would generally fail to do. Also this liquid need only be used for extremely dense flints.

Homogeneity of Liquid.

Whatever be the nature of the liquid employed, it is extremely important to keep it homogeneous by mechanical stirring. A glass "propeller blade" driven at a suitable speed in the liquid by a small electric motor will secure this condition. The motor must naturally be quite separate from the rest of the apparatus.

Adjustment and Measurement of Refractive Index of Liquid.

It has been found very convenient to use the liquid in a prism cell on the table of a spectrometer. The cell should have refracting faces of plane parallel glass, and its dimensions are dictated by the sizes of the specimens for which the instrument is required. This method would naturally be difficult to apply to large lenses.

Small departures from true parallelism in the faces of the prism will not appreciably affect the final result if the value used for the angle of the prism is that between the exterior glass faces. Assuming the walls of the cell each to act as a small prism of angle 1 minute, each increasing the deviation, also that the indices of the glass and liquid are 1.5 and 1.7 respectively, and the prism angle to be 60°, it can easily be found that the error of calculation when the whole prism is supposed homogeneous is just greater than 1 in the 4th decimal place. It will be seen that if plane parallel glass, accurate to a few seconds, is employed there will be

no need of correction. If the cell walls are not quite parallel it will be best to calculate out the error for a few particular cases from the angles and refractive index and to apply a correction from these results.

With regard to the construction of the prism cell, plaster of Paris was found to be as good a cement as any that was tried; it holds carbon disulphide very well if the ground edges of the glass are made to fit accurately, but doubtless there are better cements for the purpose.

The spectrometer should be correctly adjusted for ordinary working; the prism must be levelled and its angle determined in the usual way.

On filling the cell with liquid and illuminating the slit with a suitable source a diffuse spectrum will be seen which becomes sharply focused when the stirrer is rotated and the liquid is made homogeneous. When the specimen is immersed it will generally diffuse a good proportion of the light, but should preferably leave a faint spectrum formed by light which has passed through the liquid alone. It is best to start with pure carbon disulphide and gradually dilute with alcohol. If a hydrogen tube is used we shall see successive parts of the spectrum sharply focused, the red being first. The strength of the liquid should be adjusted so that its index is very slightly higher than the value required to focus sharply any particular line; the evaporation of the carbon disulphide, which generally disappears faster than the alcohol, will presently bring the line into focus very slowly and distinctly. At the moment of sharpest focus the angle of minimum deviation is taken in the usual way, when the refractive index of the specimen can be worked out from the formula.

It would be easy to suggest various alternative methods of determining the point at which the refractive indices are equal, and also of obtaining the refractive index of the liquid, but

the method here described has the advantage that one observation registers the angle of minimum deviation at the moment of equality. It is not necessary to observe equality with one instrument and refractive index with another, a proceeding which might lead to error, especially when using the carbon disulphide mixture. Beyond the prism cell there is nothing in the method which cannot easily be set up in the ordinary laboratory. The cell must be made specially from plane parallel glass; the ordinary liquid prism cell will not serve.

The following results illustrate the measurements made by the method:—

Specimen.	Spectrum Line.	μ	F − C	Makers' or known Values.
Partly polished Prism (Chance)	F	1.51728		
	D	1.51145		1.51182
Boro silicate crown ...	C	1.50944		
			.00784	.00799
Lens ...	F	1.51517		
4″ focus	D	1.51020		1.5108
1½ diam.	C	1.50716		
			.00801	.00806
Quartz Prism		1.5441		1.54426
Ord. & Ext. Rays ...	D	1.55308		1.55336
			ν	
Telescope Objective	C	1 5276		
(*a*) Pos. Lens	D	1 5307	51.5	—
	F	1.5379		
(*b*) Neg. Lens	C	1.6146		
	D	1.6200	36·2	—
	F	1.6317		

These values were obtained on a rough laboratory spectrometer reading to 1 minute only. Repetition of the experiments gave the same angular readings within the limits of uncertainty for the scale and vernier. It will be seen that the average error made was 1.4 in the 4th decimal place. It seems clear that with a well made prism and more accurate spectrometer, results should be given with an uncertainty considerably less.

The measurements on the telescope objective will illustrate the identification of the components. The positive lens has similar properties to a type of dispersive crown, and the negative lens to one of Chance's dense flints.

	μ_D	Mean Dispersion C−F	ν	D−F
Positive Lens 0.881 Jena ...	1.5307	.0108	51.5	.0072
Dispersive Crown ...	1.5262	.01026	51.2	.00727
Negative lens 361 Chance ...	1.6200	.0171	36.2	.0117
	1.6214	.01722	36.1	.0123

While the spectrometer gives a ready means of performing the experiment, a certain amount of calculation is naturally needed to obtain the refractive index of a specimen. In order to obviate this necessity it would be a great advantage to have a direct reading instrument. There are several liquid refractometers which read to about 1 in the 4th place, and these could be used to obtain the value of the refractive index of the liquid at the proper moment, as before suggested, but a separate observation would be necessary to register the equality, with a possible exception in the case of the Fèry refractometer made by Messrs. Hilger. A modified form of the Abbe spectrometer giving direct readings

by a special device appears to be the most likely form of instrument for the purpose, but without trial it is impossible to make any definite decision. It is hoped to test these ideas after the war, when the pressure on optical works has subsided.

Meanwhile, as has been shown, it is possible easily to obtain the optical constants of most glass specimens, except those having forms approximating to a plane parallel plate. Obviously, no indications for such a form would be yielded by this method, but the optical constants could then be found by a Pulfrich refractometer. Lenses and prisms, or rough pieces with surfaces not too flat, are easily tested; by taking apart any complex system the complete analysis of the components may be made. The necessary accuracy for such a purpose is about 2 or 3 units in the 4th decimal place.

In analysing such a system it will be as well to examine it carefully beforehand. Separations of the component lenses may be as important as their refractive indices. The exact measurement of curvatures by any suitable methods will complete the analysis.

Christiansen's Mixtures.

The phenomena observed by immersing transparent solids in liquids of similar refractive index are well illustrated by the curious mixtures described by Lord Rayleigh and Christiansen. Powdered quartz or glass when placed in a mixture of carbon disulphide and alcohol adjusted to the correct proportions transmits strongly coloured light corresponding to the wave-length for which the mixture is optically homogeneous. Light of a complementary colour is reflected.

On warming, red light is transmitted first, then yellow, green, and so on as the refractive index of the liquid changes with the rising temperature.

Detection of Faults in Unpolished Glass.

Specimens of glass can, of course, be examined for defects such as bad metal, bubbles, and veins by immersion before they are polished. The liquid should be contained in a cell having parallel sides of good plate glass. Under a strong illumination bad metal and bubbles may be easily seen in specimens when dipped into a liquid of which the refractive index has been adjusted to the correct value.

Veins are more difficult to detect, but they may be found in this way. Use a distant source of light in a comparatively darkened room. An ordinary magnifying glass forming an image of this source at the pupil of the eye will appear to be filled with light. If now the cell is brought in front of the lens, veins can generally be detected when looking through parallel faces of the specimen, even with white light. Care should be taken that the unpolished faces are free from dirt, which might be mistaken for some defect in the body of the glass, but the difference is generally easy to see.

It has recently been suggested that the usual examination of specimens for stress by means of polarised light may fail to give correct indications owing to the presence of opposite forces in adjacent parts of the glass. While, of course, it is extremely unlikely that in such a case all indications of double refraction would be entirely absent, yet it is possible that a very erroneous idea as to the amount and distribution of the stress may be gained, unless the glass is examined in more than one direction. By immersion in a bath of adjusted refractive index specimens, though unpolished, may be examined by light transmitted in any direction when the location and magnitude of the principal stresses should be observed.

SOME DIRECT READING INSTRUMENTS FOR CURVATURE.

For many purposes in the optical workshop it may be desirable quickly to test the curvature of a surface, apart from any very exact determination. There is a very useful little instrument adapted for small heavily curved lenses, consisting of a brass ring and a central plunger carrying an ivory point. This gives a measure of small radii on a scale, but fails for values greater than an inch or two. The simple instrument here described may be found of use in this connection. It is useful for convex surfaces only, but concave surfaces can easily be tested roughly by other means, such as adjusting a pair of cross wires, brightly illuminated and examined by an eyepiece, to coincide with their own image at the centre of curvature. Such an instrument could easily be made to read radii directly if a suitable scale were provided.

Virtual images such as are given by convex surfaces are hard to locate, but the path of a single ray may easily be found. The theory of the suggested apparatus is indicated by the diagram.

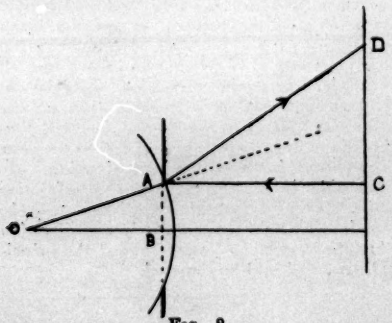

FIG. 2.

A ray CA parallel to the axis BO of the curved surface is reflected to a point D on a line CD at right angles to the line CA.

We have if $\angle$ AOB = θ,

$$\angle DAC = 2\theta.$$

Then $$\frac{DC}{AC} = \tan 2\theta$$

$$\frac{AB}{AO} = \sin \theta$$

And radius of curvature, R, $= \frac{AB}{\sin \theta}$

Where AB is the distance from A to the axis.

To calculate the value of R for given values of the other constants tan 2θ might be expressed in terms of sin θ to obtain an algebraical relation. It is easier to work out the value of tan 2θ and look up the value of θ and sin θ from Chambers' tables, whence R can be obtained. Similarly we can obtain a scale for R along CD. In the actual instrument AB is kept constant by putting the lens surface in contact with a fixed circular stop; the diameter of the circle will be equal to 2AB.

A straight slot is cut in a plane piece of wood or metal, and at one end of the slot is placed a pinhole aperture. The top of a strong box of suitable height in which a slot is made serves the purpose extremely well.

The circular stop is fixed immediately below, so that the edge of the circle is on the line from the pinhole aperture perpendicular to the top plane. A diameter of the stop must be parallel to the slot, and the plane of the circle must be parallel to the top plane. In these previsions we are simply imitating the geometrical condition of the diagram. The perpendicular ray from the pinhole will now always on reflection pass through the slot at a distance varying with

the radius of curvature in contact with the stop.

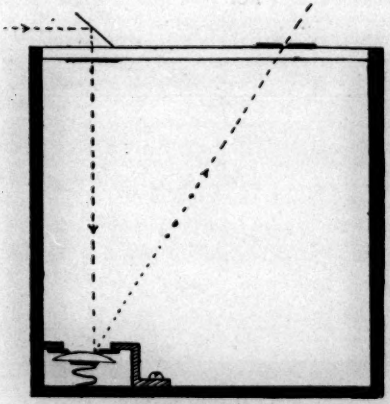

Fig. 3.

The construction and fixing of this stop are the most important things in making the instrument. The circular hole must be turned out in steel and the top edge bevelled off; the under surface should naturally be planed before the turning is done. The diameter of this stop must be measured accurately by a reading microscope. The diaphragm is then soldered to a mount of stout brass and the whole fixed to a small wooden base ready to be placed in position underneath the slot. A small piece of plane glass is pressed against the diaphragm, and the underside of the slot is brightly illuminated by an electric lamp. On looking through the slot its image in the piece of glass is seen, and this image must be made to cross a marked diameter of the diaphragm. The remaining ad-

justment is to ensure that this diameter is parallel to the slot itself. A pinhole made in tinfoil is stuck to the undersurface of the slot, so that a line from it at angles to the slot passes through the end of the marked diameter. This position for the pinhole may be found by measurement. The *image* of the pinhole seen through itself must be made to come to the same point at the edge of the circle. These necessary adjustments can easily be made by moving and wedging or cutting the wooden mount.

A small brass plate slides against a rest so that a small hole in it moves over the slot. It is best to drill a hole about 2 mm. in diameter in the brass, and underneath this to fasten a smaller pinhole in tinfoil. The instrument is now ready for the scale, which may be calculated out as indicated. When placed in position a fiducial mark on the movable indicator should indicate ∞ on the scale when the pinholes are superposed.

To obtain the radius of curvature of a surface it is lightly held against the diaphragm by a spring and the fixed pinhole illuminated from above. The bright image in the surface is viewed through the indicator, which is moved away till the image is just hidden by the edge of the stop. The fiducial mark gives the radius of curvature.

The necessary dimensions of the instrument depend on the type of curves for which it is required. For small lenses having radii from 3 to 10 cms. convenient dimensions will be:

Diam. of stop 1.5 to 2.0 cms.
Distance AC 25 to 30 cms.

For small telescope objectives, etc., with shallower curves a bigger instrument must be used,

Diam. of stop = 3 cms.
Distance AC = 100 cms.

Pendulum Curvature Apparatus.

The radius of curvature of a convex surface may also easily be found by mounting the surface on a pendulum rod so that the centre of oscillation coincides with the centre of curva-

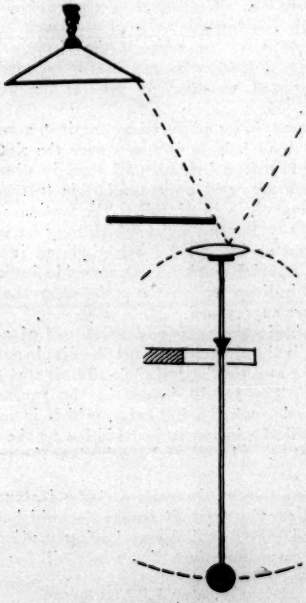

FIG. 4.

ture of the surface. Under these circumstances the vibration of the pendulum will not move the surface out of a certain spherical locus, and the images of objects formed by reflection therein will appear to be stationary.

A very simple method of observing a slight motion of the images is as follows:—Place a straight edged piece of card just above the surface so that the image of a circular electric lamp shade is nearly hidden by the image of the card. A very slight displacement of the images will result in the lengthening of the strip of shade seen.

It is convenient to fix the lens by a little wax

FIG. 5.—GENERAL ARRANGEMENT OF THE APPARATUS USED FOR REFRACTOMETRY OF LENSES, ETC.

to a small disc at the top of the pendulum rod. Place the test surface downwards on a ring on a horizontal table and have some arrangement to hold the length of the rod vertically above the centre of the ring. Bring the waxed disc down and pick up the lens.

The rod carries a scale, Zero being at the top, and passes through a short metal tube holding a clamping screw; the tube has the knife edges flush with one end.

The length of the pendulum rod above the knife edges is adjusted till the images show no variation, the scale reading given by the knife

edges plus the thickness of the lens measures the radius of curvature of the surface. The accuracy is about 1 per cent.

An alternative method of detecting any movement of the image is to view it through a short focus telescope provided with cross-wires. The distance from the knife edges to the apex of the surface may also be found with calipers or a reading microscope. Under these circumstances the mean of several results can be taken as correct to about 0.5 per cent.

Since the writing of this paper a somewhat similar method for obtaining refractive indices has been published* by Mr. R. W. Cheshire, B.A., based upon the Schlieren-method of Töpler. The adjusted refractive index of a liquid is taken by means of a Pulfrich refractometer, the results obtained being consistent within a few units of the fifth decimal place.

The comparative simplicity of the spectrometer method and its availability for direct measurement with a hydrogen vacuum tube may, however, recommend it in cases where the necessary accuracy can thus be obtained.

My thanks are due to Professor Fowler for his interest and helpful suggestions.

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* Phil. Mag., October, 1916.

A WORKSHOP METHOD OF DETERMINING THE REFRACTIVE INDEX OF A BLOCK OF GLASS, OF WHICH ONLY ONE FACE IS POLISHED.

By Dr. Reginald S. Clay.

The method is based, as are the Abbe and Pulfrich refractometers, upon the determination of the critical angle when light passes from the medium of which the refractive index is to be found, into one of which the index is known. The hemispherical ball of the Abbe, or the cube of the Pulfrich, refractometer is replaced, in my case, by an isosceles prism, which, in the instruments shown, is an isosceles right-angle prism. This must, of course, have a higher refractive index than that of the substance it is required to measure. Mine has the value 1.7172. A simple telescope, composed of two spectacle lenses with a cross-wire at their common focal plane, is used to take the readings. A drop of liquid of high refractive index (I use *Quinoline*) is placed on the hypotenuse face of the prism, and this is placed upon the polished face of the glass of which the refractive index is required. Sodium light is caused to fall on one side of the block of glass, and the light emerging from one face of the prism is received by the telescope. The latter is turned until the critical angle is obtained—shown by one-half of the field of the telescope becoming black—the dividing line of the field should be on the cross-wire of the telescope. The observation is repeated for light falling on the opposite side of the glass block, and emerging from the other face of the prism. The angular distance between the two positions of the telescope will give the refractive index of the glass. The scale can be divided to give the refractive index directly, or if it is divided into degrees, a curve can be drawn to give the refractive index when the angle is known.

A diagram, Fig. 1, will make the description clear. S is the sodium flame. The ray Sp parallel to the surface passes through the layer of liquid to Q, through the prism to R, and emerges along RT. In the second position, the light from S′ passes along S′p′Q′R′T′. The angle between RT and R′T′ is found.

It is not difficult to see how the value of n, the refractive index of the glass, can be calculated when n_0, the refractive index of the prism, is known. For in fig. 2, if MQR, the critical

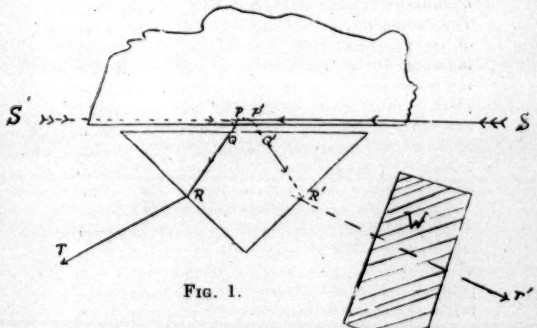


FIG. 1.

angle from the glass into the prism, is denoted by r_1, and the angles the ray makes with the normal NN to the surface AC be denoted by r and i respectively, we have

$$n = n_0 \sin r_1$$
$$\sin i = n_0 \sin r$$
$$\text{and } r_1 = 45 + r$$

Also, if θ is the angle between the two positions of the telescope, *i.e.*, betwen TR and T^{1}R^1 in fig. 1, $\theta = 2(45 + i) = 90 + 2i$. Taking θ to be 110°, 120°, ... 220°, i will be 10°, 15°, ... 65°. Subtracting the log. n_0 from the

log. sin i will give log. sin r, and therefore r. Add 45° to r to get r_1, add log. n_0 to log. sin r_1, which gives the log. n. The calculations should, of course, be tabulated. They should be carried to five figures.

A new scale can now be made, giving the refractive index directly. All that is necessary is in taking the reading s to bring the zero of the scale round to coincide with the index attached to the telescope when it is in its first position TR, and then the scale will give the refractive index n, when the telescope is in its second position T^1R^1.

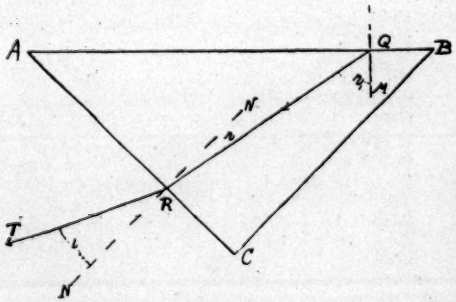


FIG. 2.

A small block of wood painted dull black is placed at W (fig. 1), when taking the reading TR, to cut off any light coming directly through the prism, or reflected at the hypotenuse face. This block is moved to the other side of the prism when taking the reading T^1R^1.

The scale is a very open one, for instance, with my prisms θ changes from 110° for n = 1.3423 to 220° for n = 1.6722. In the middle of the scale 3° changes the second figure after the decimal point by one unit. As a tenth of a degree can be estimated, it is easy to see that

even with a home-made apparatus and no vernier, the third figure beyond the decimal should be correct.

If only rough readings are wanted, a scale can be constructed experimentally by observing the angle between the two positions of the telescope with four or five specimens of glass of known refractive index, plotting the deviations obtained against the known indices, and then drawing a smooth curve through the points obtained. Even in this way there should be no difficulty in getting the third decimal within one or two units.

For my telescope, I have two tubes, one about four inches long, which slides in another about eight inches long. An eleven diopter lens is mounted in the end of each, and a cross wire in the focal plane of that in the longer tube—the objective. It is adjusted until there is no parallax between it and the image of a distant object. Then the lens end of the shorter tube is inserted in the end of the longer, and adjusted until the cross-wire is in focus. Thus the eye is about four inches from the eye-lens. The other end of the telescope should be about three inches from the prism, so that the eye and the prism may be conjugate with respect to the telescope

DISCUSSION ON PAPERS BY MR. L. C. MARTIN AND DR. R. S. CLAY.

MR. IRVINE AITCHISON asked whether Mr. Martin claimed originality for his method of determining refractive indices.

MR. MARTIN replied that he had not seen anything just like it.

MR. AITCHISON said the method was certainly used ten years ago in the Mineralogical Laboratory at Cambridge, for determining the refractive indices of small fragments of crystals.

MR. MARTIN said he had not seen it.

MR. AITCHISON, continuing, said that on the other hand Mr. Martin's method, as applied to the discovery of strains in unpolished glass, seemed to him capable of development into a practical method.

The PRESIDENT: That is not new.

MR. AITCHISON: Is it not? I have not seen it used.

The PRESIDENT asked whether Mr. Aitchison could give any further details as to the method employed at Cambridge, and said that, as so far as he was aware, Mr. Martin's method was new.

MR. AITCHISON said he was afraid he could not; it was ten years ago, and he had forgotten the details. He had, however, a distinct recollection that the method in question involved the use of carbon bisulphide and alcohol, and also the use of the spectrometer, although he did not say that it had been carried to the degree of accuracy which Mr. Martin claimed.

MR. FRANK TWYMAN said that the device of putting pieces of glass into a liquid of the same refractive index with the view of seeing something inside the glass was a familiar one, as was also the Toepler or knife-edge method of test. But he did not remember any anticipation of either Mr. R. W. Cheshire's or Mr. Martin's quite distinctive methods of applying these

devices. Both methods seemed to him practical, and they both seemed to him to meet a much-felt want. They did not, however, meet the want which he himself felt most keenly, namely, some means of quite easily and quickly measuring the refractive index fairly frequently with a considerably higher accuracy. Either method would no doubt give the refractive index to within 1 or 2 in the fourth decimal place, but one really wanted it to within 1 or 2 in the fifth decimal place, or at any rate one wanted to use means capable of that degree of accuracy.

Mr. S. D. Chalmers was most interested in the methods and results of Mr. Martin, and wished to express his appreciation of the ingenuity of the method and the care in working out the details. The author had referred to his (Mr. Chalmers') method of measuring the refractive index of glass in the form of a lens. In this method the resultant power when the lens was immersed in a suitable liquid was measured. He had used this method with considerable success, and had obtained an accuracy of 1 or 2 in the fourth decimal place, making use of three liquids only; with more careful choice of the liquids, rather greater accuracy could be obtained. He thought the method suitable for all types of lenses, except possibly those of microscope types.

In using the method he had at first employed simple cells to hold the liquid and lens, but in view of the difficulty of keeping the liquid quite constant he had made use of a prism-shaped holder, and had arranged this so that the constancy of the liquid could be checked, and if necessary the refractive index directly measured.

This arrangement had the drawback that it was much more difficult to keep the liquid uniform and free from striæ of different density, and was only used when great accuracy was required and special precautions could be taken.

He was much surprised to hear that these

difficulties of striæ, etc., could be completely overcome by mechanical stirring.

With regard to the special case where the curvatures of the surfaces were weak, he thought this problem was best dealt with by a direct measurement.

He had recently used a refractometer of the type of the Abbe crystal refractometer with some success for shallow concave and convex surfaces.

The results were nearly, but not quite, so accurate as those obtained with plane surfaces, and he would like to bring before the Society the theory and experimental results of the method.

With reference to Dr. Clay's paper, he had looked into the theory of the method, and it seemed to him that Dr. Clay was obtaining accuracy in special cases only: that his prism was specially suited for refractive indices nearly equal to that of the prism. The practical suggestion he wished to make was that, in measuring glass for optical purposes, different prisms should be used for each of the typical kinds of glass; that the glass and refractive indices of the different prisms should be chosen to give accuracy for a very small range of refractive indices. In this way the practical accuracy might, he thought, be very much increased.

He would like to call Mr. Martin's attention to a paper by Dr. Searle, Mr. Aldis, and Mr. Dobson, describing a method of measuring curvatures directly, which was based on the same principle as that described in the paper, though the apparatus was quite different.

Mr. J. W. Hasselkus said he would like to ask Mr. Martin whether he had considered the method of finding the refractive index of lenses by utilising the method of immersing the lens in a liquid and measuring the deviation from parallel of a beam of light going through the lens immersed in the liquid as compared to the beam going through the liquid itself. Very small alterations in the parallelism of beams

could be detected with very great accuracy, and he thought the method might be employed with good results.

The PRESIDENT said he had been very pleased indeed that the ethical aspect of the two papers they had heard to-night had apparently not been challenged. He dare say they all knew that if it were possible to take any particular lens system at the present moment and drop it into a tumbler of water and determine the optical data necessary for its manufacture, many warlike instruments could be made much more rapidly than now; and he was afraid that under those circumstances the end would certainly justify the means, certainly so far as he was concerned. To give them some idea of the difficulty of the problem, however, he might say that only a very short time ago he came across a rather simple and apparently not difficult optical telescope system, and he had the curiosity to make enquiries as to the number of hours which had been actually expended upon the designing and computing of the system; he found that a very capable designer and mathematician had spent more than a thousand hours in getting out the necessary construction data for that system. Now if, when the system had been computed and constructed, it had been possible to simply drop the lenses into a liquid and find out all the required data, it would have brought about a very desirable result from the point of view of the requirements of the present moment, although at the same time it might possibly be opposed to the law of morality. But the fact that so comparatively simple a system required all that amount of work did show how important it was, at a time like this, to take short cuts to practical results.

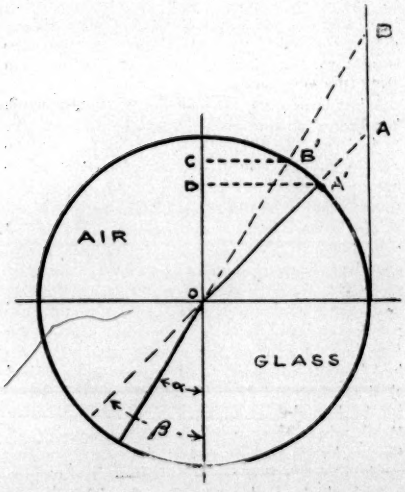
He regretted that Mr. R. W. Cheshire was not present to reply to the various criticisms passed upon his work, but he might say that the work in question was pre-war work cut short by the war itself. The paper in question was there-

fore necessarily a very incomplete one, and when Mr. R. W. Cheshire would be able to continue it he did not know; but he did know that the great difficulty he had found in connection with that work was that which Mr. Chalmers had pointed out, namely, the difficulty of getting the liquid of the required refractive index and then keeping it in a homogeneous condition until the refractive index could be determined by the refractometer. But he did not think there could be any doubt as to the extraordinary delicacy of this particular method, and the results so far obtained were in his opinion certainly very promising.

When he saw the titles of the two papers which had been read that evening, he had the curiosity to look up the history of the discovery of the simple law of refraction, and found it to be one of the most interesting and curious stories in the whole field of optics. Ptolemy, who lived in the second century of our era, determined experimentally the angles of refraction corresponding to given angles of incidence varying from 0° to 80°, for air and water, air and glass, and water and glass. And yet, although the greatest trigonometer of his time, one of the founders in fact of the science, and one who had himself constructed with great geometrical skill a complete table of sines for angles increasing by half degrees of arc, he failed to discover the simple relation existing between the sines of the angles of incidence and the corresponding angles of refraction for any given pair of media, a fact which, in his (the President's) opinion, furnished strong presumptive evidence that Ptolemy the optician was not identical with Ptolemy the geometrician. The subject of refraction was subsequently investigated by Alhazen and Vitellio with great care, but the law eluded their grasp. Then at the beginning of the 17th century the great Kepler attacked the problem, but although by assuming a constant ratio for the angles of incidence and corre-

sponding refraction, when small, he was enabled to give the first correct explanation of the optical action of a telescope, he met with little more success than his predecessors.

Finally about 1620, that is 15 centuries after Ptolemy, Snell, a professor of mathematics at Leyden, discovered the law which in England is known by his name. Snell died soon after



this and his manuscripts were unfortunately not published, with the result that the law of refraction was first given to the world by Descartes, as a discovery of his own, in the year 1637.

It should be noted, however, that Snell gave the law in terms of the cosecants of the angles of incidence and refraction. Thus let the figure show the path of a ray passing from air to glass, then according to Snell's statement of the law,

the refractive index n is related to the angles of incidence and refraction thus :—

$$n = \frac{OB}{OA} = \frac{cosec\ \alpha}{cosec\ \beta}$$

whilst Descartes gave the law in its present form thus :—

$$n = \frac{A'D}{B'C} = \frac{Sin\ \beta}{Sin\ \alpha}$$

AUTHOR'S REPLY.

Mr. Martin said that with regard to the point raised by Mr. Aitchison as to the originality of his method, it was true that Mr. R. W. Wood had described in his book on Physical Optics a similar method. He placed a powder in a liquid and observed generally one particular portion of the spectrum, by refraction through a prism cell. That, of course, might give the refractive index and dispersion to a certain degree of accuracy, but it was very doubtful whether this was equal to the accuracy which the method of mechanical stirring and proper focusing had given it. He had, of course, no other means of testing than simply taking the measurements and comparing the results obtained with the makers' known values; but those, it seemed to him, had given very sufficient proof that the method was a reliable one. With regard to Mr. Chalmers' point as to the mechanical stirring, his experience was that mechanical stirring produced a great optical homogeneity; those who were at all interested in spectroscopy would know that the iron spectrum had an immense number of lines, but by using a good spectrometer and a liquid prism this intricate spectrum could be perfectly and beautifully focused by mechanical stirring, although when the stirring ceased the definition fell off hopelessly. It was quite possible to use the iron

spectrum for the determination of refractive index. As regards previous anticipations of these methods, it was generally humorously said that we had nothing new, and that the Chinese had invented all our discoveries thousands of years ago. Seriously, it was very difficult always to know exactly what had been devised before, but for simple workshop use he thought there was at least no harm done in proposing these methods. He had tried his best to find out whether they had been previously proposed, but with negative results. With regard to the method suggested for detecting any difference in refractive index, by a deviation from the parallel nature of the beam of light, that was of course really what was done in the spectrometer method, by passing a parallel beam through the prism cell; the component parts were each still parallel after dispersion and one was observing the deviation from the parallel beam. There were a number of ways in which the equality might be observed. Pushed back to the limit really Mr. R. W. Cheshire's method and his own were similar to a great extent. The difficulty with the liquid, as the President had observed, if mechanical stirring was not adopted, was very great, but he thought Mr. R. W. Cheshire had overcome it fairly successfully. He believed he had placed a cover over the cell, and found that in due time the evaporation of the liquid produced a steady state. That, of course, was a matter of time. One of the advantages of using the spectrometer method was that one did not have to wait; the mechanical stirring seemed to produce the required homogeneity very quickly.

Dr. Clay said that with regard to the point Mr. Twyman had raised, although the apparatus he had shown was very simple and cheap, he believed that as he read a double angle instead of reading from a zero in one direction only so that total reading was double that of the Pulfrich refractometer, an instrument pro-

perly constructed with a good lens and so on ought to give an accuracy twice as high as the Pulfrich. Mr. Chalmers had said that from theory the accuracy might be much increased by using different prisms for different types of glass. If they examined the instrument shown they would see that the scale opened out as the index measured approached that of the prisms itself, and in calculating the scale it would be found that the curves ran up so that when getting towards the refractive index of the prism a very small change in the refractive index which was being measured corresponded to a very wide graduation on the scale. Thus Mr. Chalmers was undoubtedly right in saying that by choosing prisms with a refractive index just a little higher than that of the glass which was required to be measured, a high order of accuracy could be obtained. He would like to mention just one other point, namely, that a very small specimen could be used for this purpose. He had often, in using the instrument, had only enough liquid on the face of the prism to give a spot something like $\frac{1}{8}$-inch in diameter, and he had been able by placing his eye just at the conjugate focus of that spot, to measure the refractive index of that tiny quantity of liquid. That might sometimes be useful to a chemist if he could only get a very small quantity of a liquid, but he mentioned it chiefly as if one was given a lens and wanted to find the refractive index; all that need be done was to polish a little flat on the edge of the lens $\frac{1}{8}$-inch in diameter, and the refractive index of that lens could be found.

The PRESIDENT, in proposing a vote of thanks to the readers of the papers, said they had had a very interesting subject dealt with in a very interesting manner. There could be no question as to the value of papers of that kind; they gave a great deal of valuable information, and one desirable thing they certainly did was to disabuse their minds of that notion they so

often got when studying the catalogues of scientific instrument makers—that instruments of precision could not be produced with any but expensive methods. It was always refreshing and invigorating to find that accurate results could be obtained by very simple means. At the same time he quite appreciated and sympathised with Mr. Twyman's criticism.

Before sitting down he would like to remind them again that the next meeting of the Society, on January 11th, would take the form of an exhibition of workshop optical testing apparatus. The success of that exhibition, he thought he might say, was already assured, because Mr. Twyman had undertaken to bring to that meeting what he was afraid was an expensive piece of apparatus, but nevertheless an exceedingly interesting one, namely, an interferometer apparatus, by means of which bad glass was made into good—a very important problem at the present time. And further, he might say that Mr. Hasselkus, not to be outdone, was going to bring an apparatus by which he would prove that there was not such a thing as a bit of good glass in the world. (Laughter.)

ON A PRECISION METHOD OF UNITING OPTICAL GLASS—THE UNION OF GLASS IN OPTICAL CONTACT BY HEAT TREATMENT.—R. G. PARKER, B.Sc., A.C.G.I., and A. J. DALLADAY. (**TRANS. FARADAY SOC.**, December, 1916).

THE authors describe a new method of permanently joining two or more pieces of glass or fused silica without the use of any cement. The pieces are caused to become one mass in the following manner:—Their surfaces are optically worked so plane, or so nearly of the same curvature, that they will go into good optical contact; they are then subjected to carefully controlled heating for a given period, being held together by slight pressure. The use of cement, with its attendant disadvantages of strain, liability to perish, and lack of accuracy, is therefore avoided.

The temperature employed is always some 60-70° C. below the annealing point; this latter is determined for every kind of glass used, by examining it for the effect on transmitted polarised light (by means of a Babinet compensator) while it is being heated in an electric tube furnace having double silica windows. The strain caused by unequal heating suddenly disappears over a short range of temperature, which is the *annealing* temperature in that all internal stress vanishes, and if sufficiently slowly cooled from this temperature the glass will be perfectly annealed.

At this annealing point glass is still hard and extremely viscous; yet, accurately worked, optical surfaces may be deformed, especially if any clamping apparatus is used. Therefore a slightly lower temperature is employed, although it is always taken as high as possible to obtain the most rapid joining. The authors show that the "hardness" of a glass near its

annealing point becomes doubled for each successive fall of temperature of a few degrees, so that at 60° C. below this temperature it has become hard enough to withstand even very great local pressure for short periods.

Under the above conditions it is found that two pieces of glass will unite perfectly in one hour, at 400-600° C. while silica joins at 1,030° C. The temperature is raised gradually for 4 to 6 hours, and cooling should be equally slow. The slight pressure employed is largely in order to keep the component parts together should they come out of contact during the heating.

Articles of this solid construction break as one piece; a crack or a diamond cut passes through the junction without hindrance or deflection. It is not possible to separate the surfaces by any of the means which rapidly separate surfaces in ordinary optical contact, viz., mechanical force, the action of liquids, or sudden small temperature changes.

Since there is no deformation or softening of the glass, such articles can be made with unsupported optically worked surfaces *inside* the solid block, as in the case of absorption cells and polarimeter tubes; and as the accuracy of parallelism of the components is unchanged by the heating, it is not difficult to ensure that the windows of such cells shall be parallel to one second—an exceedingly small error.

Finally, if the components are all of one kind of glass, are put into optical contact while at the same temperature, and are slowly heated and slowly cooled, strain will be almost entirely absent from the resulting composite mass.

The union of two different kinds of glass by this method is complicated by three factors. (1) The temperature expansion coefficients will usually differ; this will cause two such pieces of glass in optical contact to come apart while the temperature is being raised, but if they are under pressure they will go back into contact when the temperature is constant at its maxi-

mum and will join. When they cool, as one piece, strain will appear owing to different amounts of contraction; it is obvious that such strain cannot be eliminated by annealing, but for many purposes it does not matter.

(2) The annealing points of optical glasses vary by 200° C. or more: therefore it is possible to select many pairs the softer of which will deform at a temperature too low for the harder to unite in any reasonable time. The annealing points of any pair chosen should not differ by more than 50° C.

(3) Certain kinds of glass which will not fuse together readily in the blowpipe flame cannot be united by the new method.

The union of different kinds of glass is important, as the authors indicate in the case of a polarimeter tube made of ordinary glass tubing of soft soda-lime glass; windows of optical plate glass were successfully put on to the ends. A one-piece object-glass has not yet been successfully prepared, owing to the number of factors which limit the glasses which may be used. Ordinary flint and crown glasses cannot be joined, as their annealing points differ too much.

During the heating of two pieces of glass in contact, the authors usually found that small spots, or areas of no contact, were liable to appear. It was discovered that they contained gas under pressure, and developed from excessively minute particles left on the glass surfaces by the cloth used for the final dusting. Owing to the difficulty of avoiding them entirely, it appears advisable where possible to have narrow areas of contact; the gas then usually escapes by reaching one edge, and the surfaces go back into complete contact.

A series of ten figures shows cells and a polarimeter tube made by this method; the large amount of strain which may be produced by cements; the complete distinction between surfaces in ordinary optical contact, and joined

surfaces, as revealed by the path of a fracture: and, lastly, a very interesting illustration of the fact that ground glass surfaces act as if they are in compression. A cell was made by drilling through a plate of plane parallel glass, and, after retouching the surfaces, putting on windows in optical contact, at each end of the drilled aperture. The rough walls of the hole pushed up a burr round its edge, traces of which remained after retouching, and by producing local pressure caused the union to be very complete over its surface, and less complete over that adjacent to it. By reflected light from the interface the effects of this burr are clearly visible.

R. G. P.

A New Method of Measuring the Refractive Index and Dispersion of Glass in Lenticular or Other Forms based upon the "Schlieren-methode" of Töpler, by R. W. Cheshire, B.A. (**PHIL. MAG.**, Vol. xxxii. October, 1916).

The method of refractometry outlined in this paper was devised with a view to the examination of specimens of glass in lenticular or other forms to which the more usual methods at one's disposal are not immediately applicable. The glass under examination is immersed in a liquid whose refractive index for the specified wave length may be varied continuously until an equality has been reached between the index of the glass and that of the liquid. The refractometric examination of the immersion fluid is then conducted in the usual manner on the Pulfrich refractometer, and it is claimed for the method that the accuracy with which this balance of indices can be realised is at least equal to the accuracy with which the refractive index of the immersion fluid can be subsequently determined on the refractometer.

The "Schlieren-methode" invented by Töpler affords an extremely sensitive means of detecting the presence in an otherwise homogeneous transparent medium of striæ or other optical non-homogeneity, and is therefore well suited to the present purpose. The arrangement of the apparatus employed is shown diagrammatically in plan below.

A vertical straight edge behind which is placed a source of monochromatic light A is

represented in plan by B. An image B′ of this straight edge is projected by means of a telescope objective C (focal length 125 cm., aperture 8 cm.) into the plane of a second straight edge, F, disposed as shown in front of an observing telescope H, [illegible] to cover about one-half of the full aperture of its objective G. The various parts of the apparatus are mounted rigidly in any convenient manner, and the two edges and the observing telescope H should be approximately centred with the axis of the principal lens C. The observing telescope, situated at a distance of roughly 5 meters from the lens C, has an aperture of about 3.5 cm. and a magnifying power—in normal adjustment—of ×24. The edge F is secured to a rack-and-pinion motion providing for a slow transverse movement across the front of the observing telescope in a right or left-hand direction. The desired parallelism of the two edges may be checked either by removing the eyepiece of the observing telescope and looking down the tube, or by examining with a small pocket magnifier the images of the two edges projected into the Ramsden circle of the telescope. A small rectangular glass cell, E, containing the immersion fluid and the glass under test, K, is adjusted in the usual way on the prism D of the refractometer (not shown in diagram), which is placed just in front of the lens C and at such a height that the cell is approximately opposite the centre of the lens. Suppose, for the sake of simplicity, that a prism of small angle is being examined and that it is immersed in the fluid contained in the cell with its refracting edge vertical. In general the refractive indices of the glass prism and the surrounding liquid will differ, and the glass will therefore exert a prismatic effect upon light passing through it. The image of the edge B will therefore present a doubled appearance, the image formed by light passing through the glass being displaced laterally by a small amount relatively to the rest of the image de-

pending upon the magnitude of the difference between the two indices. Consequently, on traversing slowly the edge F across the objective of the observing telescope, which will be supposed to be focused upon the prism, it will be found that the surface of the prism gradually darkens and finally becomes completely black, whilst the side faces and the rest of the cell will show up brightly. On continuing the steady motion of the edge F these faces also will begin to darken, until finally no light passes into the observing telescope and the whole field appears black. The order of these two phenomena is determined by the sign of the difference of the refractive indices of the fluid and prism. If now the refractive index of the immersion fluid be changed somewhat, it will be at once obvious, from the relative interval at which these phenomena occur, whether the difference in the refractive indices has been increased or decreased by the alteration. In the course of a few trials it will be found possible so to adjust the refractive index of the liquid, that on moving the edge slowly across the observing telescope the whole field, including the faces of the prism and those of the cell to the right and to the left of the prism, darkens simultaneously and uniformly. Under these circumstances the prism clearly no longer exerts any prismatic action—in other words, an equality between the indices has been attained, and a reading for the refractive index of the liquid as it stands upon the Pulfrich prism may be taken at once.

The cell employed was of rectangular form with approximate dimensions $5 \times 2 \times 1\frac{1}{2}$ cm. with optically worked side walls ($5 \times 1\frac{1}{2}$ cm.), and a base plate also optically worked, with guaranteed parallelism of sides of about $5''$. A number of immersion fluids have been tried, and that found of greatest general utility was an aqueous solution of mercury potassium iodide, whose refractive index for the D-line may be varied continuously by the addition of water

from about 1.72 down to 1.33. If this solution be exposed to the air its superficial concentration gradually changes, leading to the development of striæ within the liquid, and it was found necessary to provide the cell with a vaseline cover-plate in order to secure equilibrium within the cell, and thus to prevent the introduction of this disturbing factor.

It has not hitherto been found practicable to obtain readings for the G′-line owing to the marked absorption of the iodide solution for light at the blue-end of the spectrum. This property is characteristic of many of the highly refractive liquids, and recourse must be had to the mercury and cadmium lines to complete the examination of the dispersion properties of the glass under test. The ordinary soda flame provides all the light that is required for the satisfactory determination of the refractive index for the D-line. Results are given for the examination of a piece of glass in which the mean value for the refractive index for the D-line obtained by the method of this paper agrees with that given by a direct measurement on the refractometer to an accuracy of 2 units in the fifth decimal place.

R. W. C.